Measurement of Source Chaoticity for Particle Emission in Au+Au Collisions at $\sqrt{s_{NN}} = 130$ GeV using 3-Particle HBT Correlations

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Data from the first physics run at the Relativistic Heavy-Ion Collider at Brookhaven National Laboratory from the STAR experiment have been analyzed using three-pion correlations to study whether pions are emitted independently at freezeout. We have made a high-statistics measurement of the three-pion correlation function and calculated the normalized three-particle correlator to obtain a quantitative measurement of the degree of chaoticity in the freeze-out environment.

1. Introduction

Two-pion Hanbury Brown and Twiss (HBT) interferometry in principle provides a means of extracting the space-time evolution of the pion source at freeze-out produced in relativistic heavy-ion collisions [1,2]. An underlying assumption of this method is that pions are produced from a completely chaotic source, i.e. a source in which the hadronized pions are created with random quantum particle production phases. Although two-pion HBT provides some estimation of this chaoticity, a better method is available using three-particle correlations. Normalizing the three-pion correlation function appropriately by the two-pion correlator, the effects from particle misidentification and decay contributions can be made to drop out [3], thereby isolating possible coherence effects in the particle emission process. The resulting three-pion correlator r_3 provides the means of extracting the degree of source chaoticity by examining its value at zero relative momentum.

2. Derivation of Chaoticity from Normalized Three-pion Correlator

The measured observable in this analysis is the normalized three-pion correlator [3]:

$$r_3 (Q_3) = \frac{(C_3 (Q_3) - 1) - (C_2 (Q_{12}) - 1) - (C_2 (Q_{23}) - 1) - (C_2 (Q_{31}) - 1)}{\sqrt{(C_2 (Q_{12}) - 1) (C_2 (Q_{23}) - 1) (C_2 (Q_{31}) - 1)}} \tag{1}$$

Here $Q_3 = \sqrt{Q_{12}^2 + Q_{23}^2 + Q_{31}^2}$ and $Q_{ij} = \sqrt{-(p_i - p_j)^2}$ are the standard invariant relative momenta which can be computed for each pion triplet from the three measured momenta $(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)$. $C_2 (p_1, p_2) = \frac{P_2(p_1, p_2)}{P_1(p_1)P_1(p_2)}$ and $C_3 (p_1, p_2, p_3) = \frac{P_3(p_1, p_2, p_3)}{P_1(p_1)P_1(p_2)P_1(p_3)}$, where P represents the momentum probability distribution.

For fully chaotic sources r_3 approaches 2 as all relative momenta (and thus Q_3) go to zero. If the source is partially coherent, a relationship can be established between the limiting value of the three-pion correlator at $Q_3 = 0$ and the chaotic fraction ε ($0 \leq \varepsilon \leq 1$) of the single-particle spectrum [3]:

$$\frac{1}{2} r_3 (Q_3{=}0) = \sqrt{\varepsilon}\, \frac{3 - 2\varepsilon}{(2{-}\varepsilon)^{3/2}}. \tag{2}$$

Chaotic fraction ε gives an upper limit on the value of the two-pion λ parameter, which is sensitive to the number of coherent pairs in a sample.

The three-boson correlation function $C_3 (Q_3)$ is calculated from the data by taking the ratio $\frac{A(Q_3)}{B(Q_3)}$ and normalizing it to unity at large Q_3. Here $A (Q_3) = \frac{dN}{dQ_3}$ is the three-pion distribution as a function of the invariant three-pion relative momentum, integrated over the total momentum of the pion triplet as well as all other relative momentum components. It is obtained by taking three pions from a single event, calculating Q_3, and binning the results in a histogram. $B (Q_3)$ is computed by taking a single pion from three separate events.

3. Experimental Results and Discussion

Data for the present results are from 1M events taken during the Year-1 physics run at STAR using the Time Projection Chamber (TPC) [4] as the primary tracking detector. Two multiplicity classes were created by taking the 12% most central for the high multiplicity set, the next 20% most central for the low multiplicity set. For both multiplicity bins, tracks were constrained to have p_T in the range $0.125 < p_T < 0.5\,\text{GeV}/c$, and pseudorapidity $|\eta| < 1.0$. In the range $0 < Q_3 < 120\,\text{MeV}/c$, approximately 150 million triplets were included in both the negative and positive pion studies.

The C_2 correlation function was corrected for Coulomb repulsion with a finite Gaussian source approximation [5]. The C_3, correction factor is the product of three two-pion correction terms, obtained from the three pairs from the triplet.

In calculating r_3, the actual binned values of the correlation function for the various values of Q_3 are used instead of a fit [6]. Q_3, Q_{12}, Q_{23} and Q_{31} are calculated from triplets of particles from the dataset and the three pairs that can be formed from the triplet. Eq. (1) is then evaluated (as a function of Q_3) using the binned two- and three-pion correlation functions, and averaged over the number of triplets in each Q_3 bins.

The results for the three multiplicity bins are shown in Figures 1 (π^-) and 2 (π^+), plotted as functions of Q_3^2, and fitted to a function of the form:

$$r_3 (Q_3) = r_3(0) - C_1\, Q_3^2 - C_2\, Q_3^4. \tag{3}$$

This functional form is suggested by the theoretical analysis in [3] which shows that the leading relative momentum dependencies in the numerator and denominator of Eq. 1 are in even powers of Q_3 [7]. The fit range used is $0 < Q_3 < 120\,\text{MeV}/c$.

The resulting intercepts $r_3(0)$ are shown in Fig. 3, along with the results of WA98 and NA44. NA44 reported a result close to unity for Pb-Pb interactions, but a much lower result for S-Pb [8], both with no clear Q_3 dependence. WA98 also reported a result close to unity at $Q_3 = 0$ for Pb+Pb, and the Q_3-dependence in their result is similar to what we see in central collisions [9].
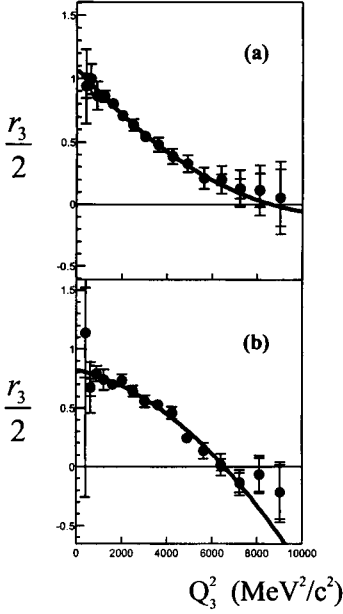
Figure 1. r_3 calculation for (a) central and (b) mid-central π^- events. The fits shown use Eq. 3 to determine the intercept. Statistical and statistical+systematic errors are shown.
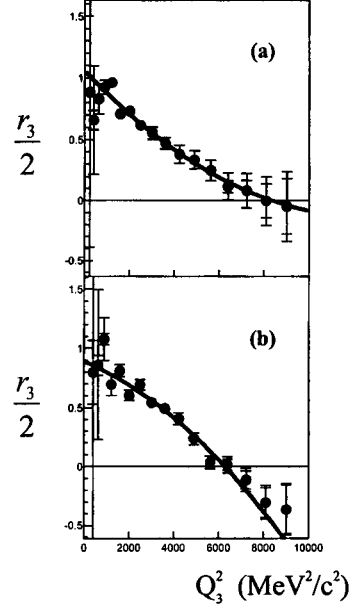
Figure 2. r_3 calculation for (a) central and mid-central π^+ events. The fits shown use Eq. 3 to determine the intercept. Statistical and statistical+systematic errors are shown.

Figure 4 shows the calculation of ε for STAR's measurements, and for those from WA98 and NA44. The plot shows a systematic trend in the STAR results going from the peripheral bin to the central bin, with the central results showing a fully chaotic source. By calculating the number of coherent pair in the dataset from the chaotic fraction, a maximum value of the two-pion λ factor has been determined which is consistent with the value of λ found in the two-pion analysis [10].

4. Conclusion

In summary, we have presented three-pion HBT results for $\sqrt{s_{NN}} = 130\,\text{GeV}$ data at STAR, and have shown that for the two multiplicity classes the STAR data indicate a large degree of chaoticity in the source at freeze-out. High statistics from STAR have allowed a normalized three-pion correlator calculation that extends to 120 MeV/c in Q_3, and when used in conjunction with the formalism of partially coherent sources obtained from [3], quantitative limits on the fraction of chaoticity are obtained which are in agreement with two-pion λ parameter measured at STAR. STAR's measured values provide increased
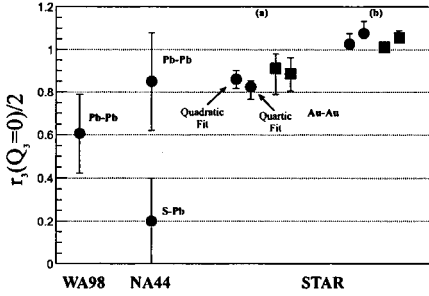
Figure 3. Asymptotic value of r_3 from STAR and two other experiments [8,9]. For STAR, central (a) and mid-central results are shown for π^- (circular markers) and π^+ (square markers) data. For each STAR dataset, separate markers denote a fit using Eq. 3 (Quartic) and a fit to a quadratic equation (Quadratic).
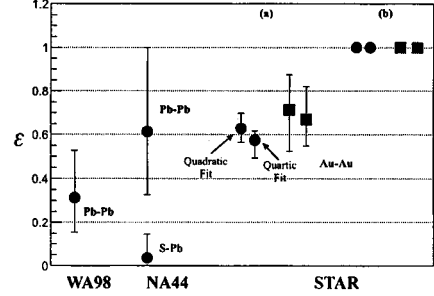
Figure 4. Chaotic fraction, calculated from Eq. 2, and plotted for the same experiments as in Figure 3. The data markers are described in Figure 3.

confidence in the validity of standard HBT analyses based on the assumption of a chaotic source.

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7. For a fully chaotic source ($\varepsilon = 1$), the leading quadratic relative momentum dependencies in the numerator and denominator of Eq. 1 cancel, if the ratio is taken pointwise in 9-dimensional $(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)$ space. If numerator and denominator are first projected on the single variable Q_3, this cancellation in the ratio is spoiled. For partially coherent sources there is no such cancellation to begin with [3]. The parametrization in Eq. (3) thus captures the expected leading Q_3 dependence of the data (U. Heinz, private communication).
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